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High-Performance DDR2 SDRAM Interface Data Capture Using ISERDES and OSERDES

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Summary

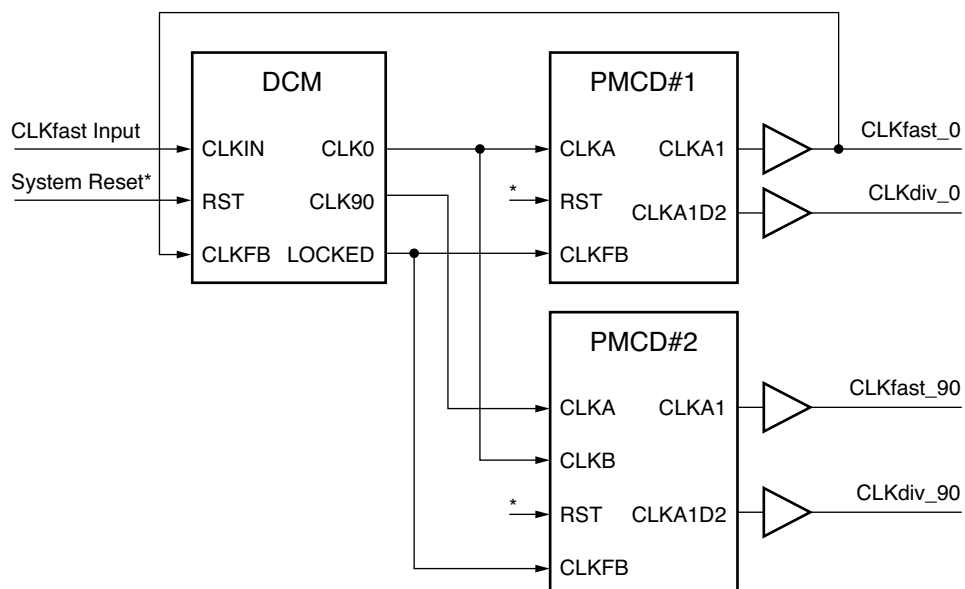
This application note describes a data capture technique for a high-performance DDR2 SDRAM interface. This technique uses the Input Serializer/Deserializer (ISERDES) and Output Serializer/Deserializer (OSERDES) features available in every Virtex™-4 I/O. This technique can be used for memory interfaces with frequencies of 267 MHz (533 Mb/s) and above.

Introduction

A DDR2 SDRAM interface is source-synchronous where the read data and read strobe are transmitted edge-aligned. To capture this transmitted data using Virtex-4 FPGAs, either the strobe or the data can be delayed. In this design, the read data is captured in the delayed strobe domain and recaptured in the FPGA clock domain in the ISERDES. The received serial, double data rate (DDR) read data is converted to 4-bit parallel single data rate (SDR) data at half the frequency of the interface using the ISERDES. The differential strobe is placed on a clock-capable IO pair in order to access the BUFIO clock resource. The BUFIO clocking resource routes the delayed read DQS to its associated data ISERDES clock inputs. The write data and strobe transmitted by the FPGA use the OSERDES. The OSERDES converts 4-bit parallel data at half the frequency of the interface to DDR data at the interface frequency. The controller, datapath, user interface, and all other FPGA slice logic are clocked at half the frequency of the interface, resulting in improved design margin at frequencies of 267 MHz and above.

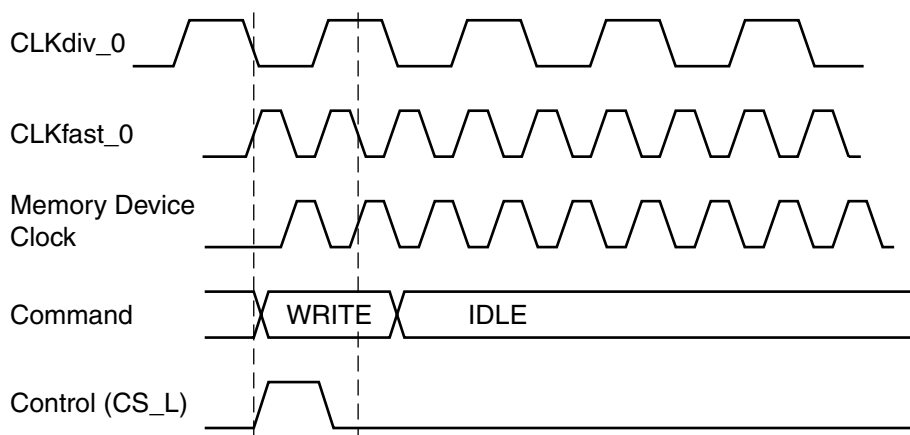
Clocking Scheme

The clocking scheme for this design includes one digital clock manager (DCM) and two phase-matched clock dividers (PMCDs) as shown in [Figure 1](#). The controller is clocked at half the frequency of the interface using CLKdiv_0. Therefore, the address, bank address, and command signals (RAS_L, CAS_L, and WE_L) are asserted for two clock cycles (known as "2T" timing), of the fast memory interface clock. The control signals (CS_L, CKE, and ODT) are twice the rate (DDR) of the half frequency clock CLKdiv_0, ensuring that the control signals are asserted for just one clock cycle of the fast memory interface clock. The clock is forwarded to the external memory device using the Output Dual Data Rate (ODDR) flip-flops in the Virtex-4 I/O. This forwarded clock is 180 degrees out of phase with CLKfast_0. [Figure 2](#) shows the command and control timing diagram.



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Figure 1: Clocking Scheme for the High-Performance Memory Interface Design

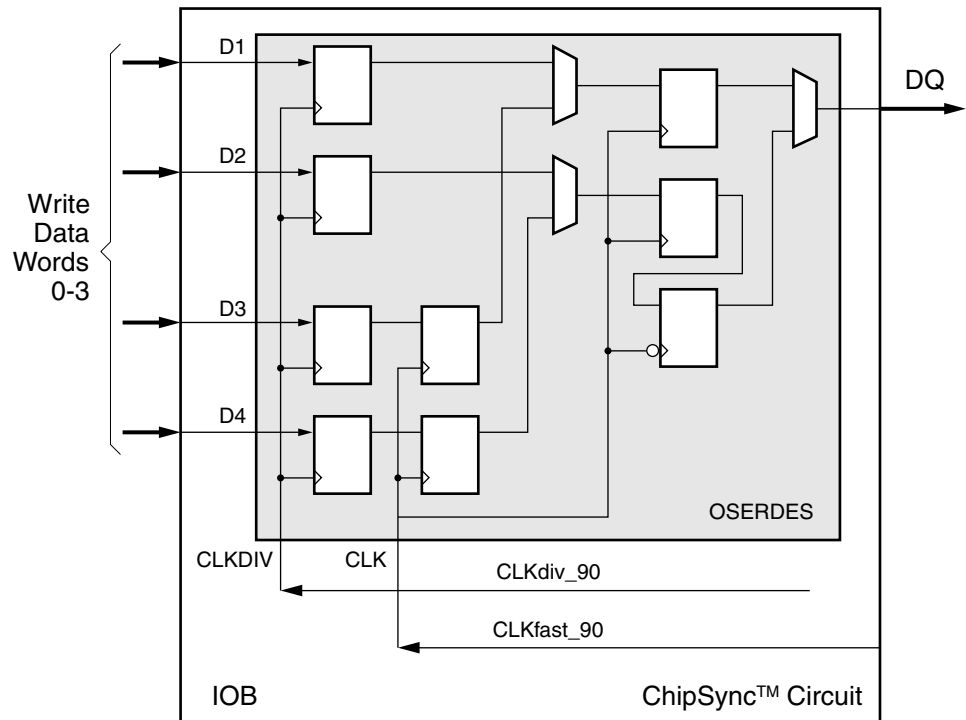


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Figure 2: Command and Control Timing

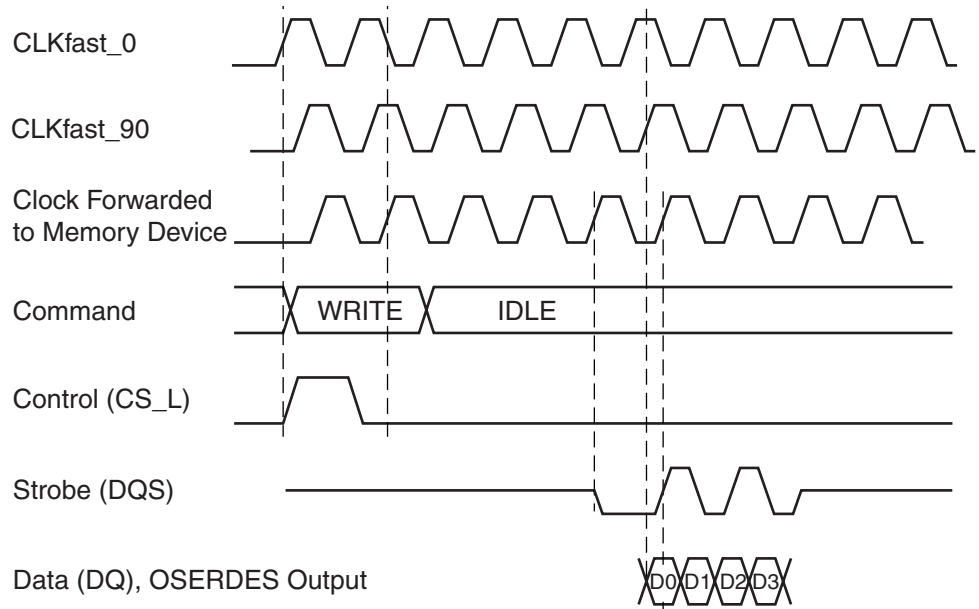
Write Datapath

The write datapath uses the built-in OSERDES available in every Virtex-4 I/O. The OSERDES transmits the data (DQ) and strobe (DQS) signals. The memory specification requires DQS to be transmitted center-aligned with DQ. The strobe (DQS) forwarded to the memory is 180 degrees out of phase with CLKfast_0. Therefore, the write data transmitted using OSERDES must be clocked by CLKfast_90 and CLKdiv_90 as shown in Figure 3. The timing diagram for write DQS and DQ is shown in Figure 4.



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Figure 3: Write Data Transmitted Using OSERDES



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Figure 4: Write Strobe (DQS) and Data (DQ) Timing for a Write Latency of Four

Write Timing Analysis

Table 1 shows the write timing analysis for an interface at 333 MHz (667 Mb/s).

Table 1: Write Timing Analysis at 333 MHz

Uncertainty Parameters	Value	Uncertainties before DQS	Uncertainties after DQS	Meaning
T_{CLOCK}	3000			Clock period.
$T_{\text{MEMORY_DLL_DUTY_CYCLE_DIST}}$	150	150	150	Duty-cycle distortion from memory DLL is subtracted from clock phase (equal to half the clock period) to determine $T_{\text{DATA_PERIOD}}$.
$T_{\text{DATA_PERIOD}}$	1350			Data period is half the clock period with 10% duty-cycle distortion subtracted from it.
T_{SETUP}	100	100	0	Specified by memory vendor.
T_{HOLD}	175	0	175	Specified by memory vendor.
$T_{\text{PACKAGE_SKEW}}$	30	30	30	PCB trace delays for DQS and its associated DQ bits are adjusted to account for package skew. The listed value represents dielectric constant variations.
T_{JITTER}	50	50	50	Same DCM used to generate DQS and DQ.
$T_{\text{CLOCK_SKEW-MAX}}$	50	50	50	Global Clock Tree skew.
$T_{\text{CLOCK_OUT_PHASE}}$	140	140	140	Phase offset error between different clock outputs of the same DCM.
$T_{\text{PCB_LAYOUT_SKEW}}$	50	50	50	Skew between data lines and the associated strobe on the board.
Total Uncertainties		420	495	
Start and End of Valid Window		420	855	
Final Window			435	Final window equals 855 – 420.

Notes:

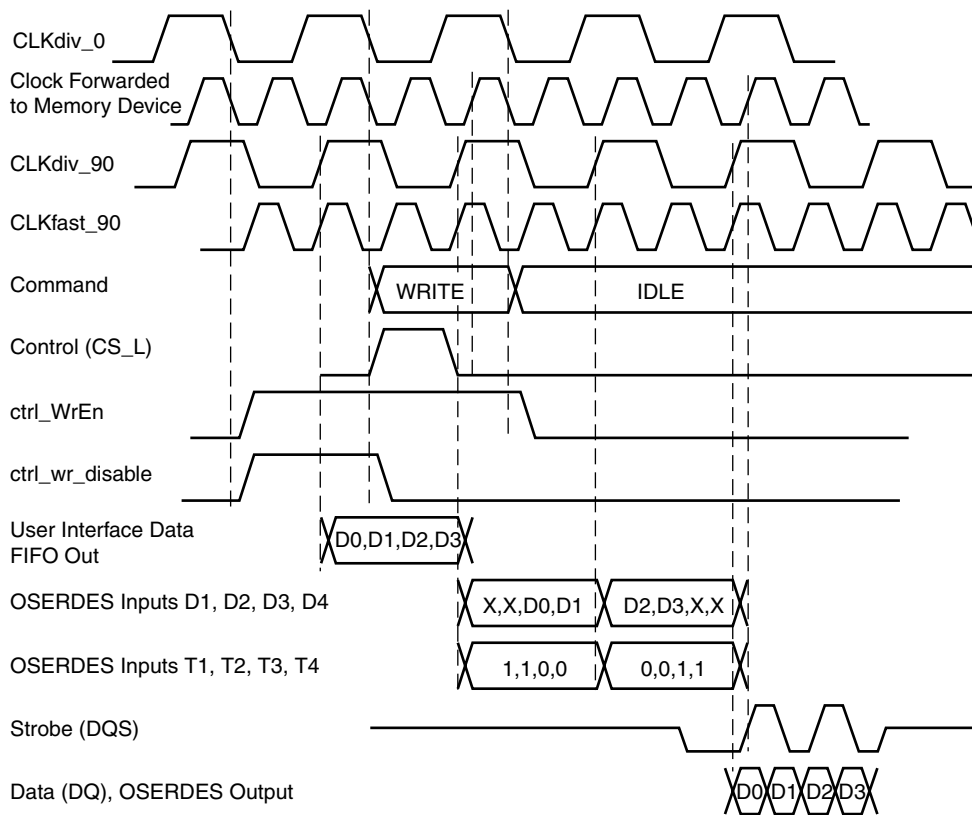
- Skew between output flip-flops and output buffers in the same bank is considered to be minimal over voltage and temperature.

Controller to Write Datapath Interface

Table 2 lists the signals required from the controller to the write datapath.

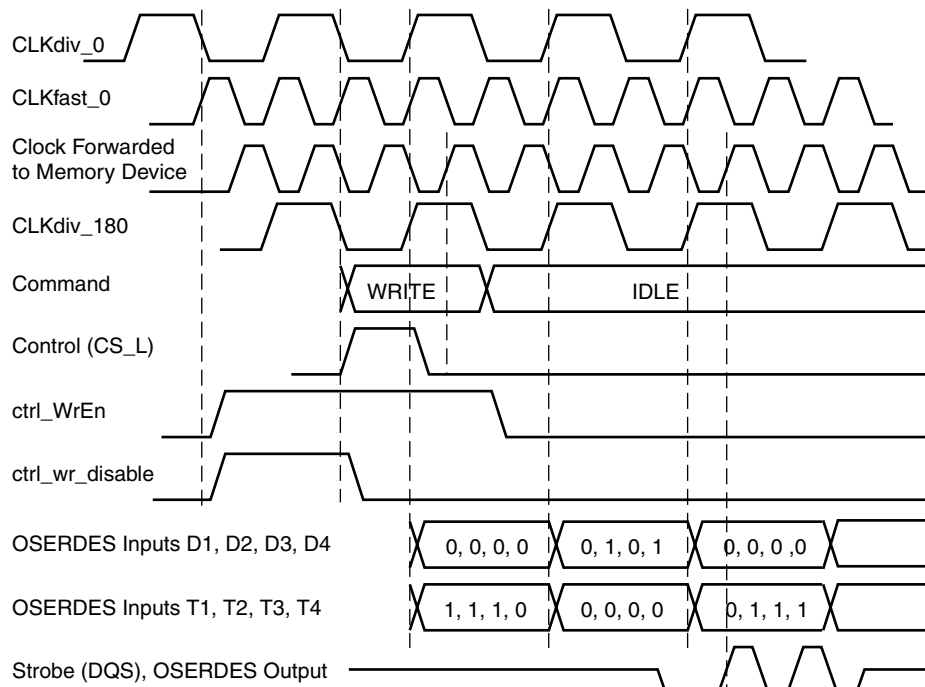
Table 2: Controller to Write Datapath Signals

Signal Name	Signal Width	Signal Description	Notes
ctrl_WrEn	1	Output from the controller to the write datapath. Write DQS and DQ generation begins when this signal is asserted.	Asserted for two CLKDIV_0 cycles for a burst length of 4 and three CLKDIV_0 cycles for a burst length of 8. Asserted one CLKDIV_0 cycle earlier than the WRITE command for CAS latency values of 4 and 5. Figure 5 and Figure 6 show the timing relationship of this signal with respect to the WRITE command.
ctrl_wr_disable	1	Output from the controller to the write datapath. Write DQS and DQ generation ends when this signal is deasserted.	Asserted for one CLKDIV_0 cycle for a burst length of 4 and two CLKDIV_0 cycles for a burst length of 8. Asserted one CLKDIV_0 cycle earlier than the WRITE command for CAS latency values of 4 and 5. Figure 5 and Figure 6 show the timing relationship of this signal with respect to the WRITE command.
ctrl_Odd_Latency	1	Output from controller to write datapath. Asserted when the selected CAS latency is an odd number, e.g., 5. Required for generation of write DQS and DQ after the correct write latency (CAS latency – 1).	



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Figure 5: Write DQ Generation with a Write Latency of 4 and a Burst Length of 4



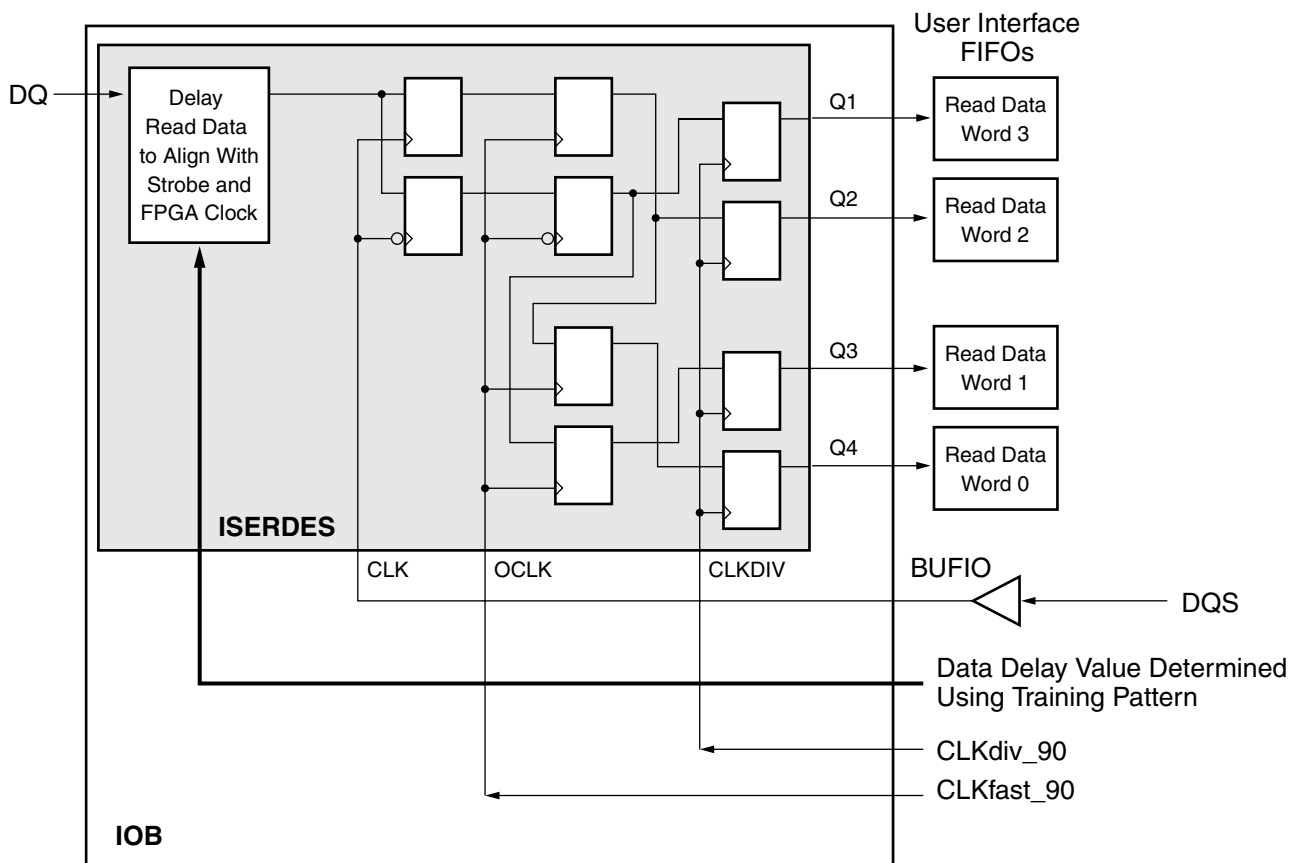
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Figure 6: Write DQS Generation for a Write Latency of 4 and a Burst Length of 4

Read Datapath

The read datapath comprises the read data capture and recapture stages. Both stages are implemented in the built-in ISERDES available in every Virtex-4 I/O. The ISERDES has three clock inputs: CLK, OCLK, and CLKDIV. The read data is captured in the CLK (DQS) domain, recaptured in the OCLK (FPGA fast clock) domain, and finally transferred to the CLKDIV (FPGA divided clock) domain to provide parallel data.

- **CLK:** The read DQS routed using BUFIO provides the CLK input of the ISERDES as shown in Figure 7.
- **OCLK:** The OCLK input of ISERDES is connected to the CLK input of OSERDES in hardware. In this design, the CLKfast_90 clock is provided to the ISERDES OCLK input and the OSERDES CLK input. The clock phase used for OCLK is dictated by the phase required for write data.
- **CLKDIV:** It is imperative for OCLK and CLKDIV clock inputs to be phase-aligned for correct functionality. Therefore, the CLKDIV input is provided with CLKdiv_90 that is phase-aligned to CLKfast_90.



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Figure 7: Read Data Capture Using ISERDES

Read Timing Analysis

To capture read data without errors in the ISERDES, read data and strobe must be delayed to meet the setup and hold times of the flip-flops in the FPGA clock domain. Read data (DQ) and strobe (DQS) are received edge-aligned at the FPGA. The differential DQS pair must be placed on a clock-capable IO pair in order to access the BUFIO resource. The received read DQS is then routed through the BUFIO resource to the CLK input of the ISERDES of the associated data bits. The delay through the BUFIO and clock routing resources shifts the DQS to the right with respect to data. The total delay through the BUFIO and clock resource is 595 ps in a -11 speed grade device and 555 ps in a -12 speed grade device.

Table 3 shows the read timing analysis at 333 MHz required to determine the delay required on DQ bits for centering DQS in the data valid window.

Table 3: Read Timing Analysis at 333 MHz

Parameter	Value (ps)	Meaning
T_{CLOCK}	3000	Clock period.
T_{PHASE}	1500	Clock phase for DDR data.
$T_{\text{SAMP_BUFIO}}$	350	Sample Window from Virtex-4 data sheet for a -12 device. It includes setup and hold for an IOB FF, clock jitter, and 150 ps of tap uncertainty.
$T_{\text{BUFIO_DCD}}$	100	BUFIO clock resource duty-cycle distortion.
$T_{\text{DQSQ}} + T_{\text{QHS}}$	580	Worst case memory uncertainties that include VT variations and skew between DQS and its associated DQs. Because the design includes per bit deskew, realistically only a percentage of this number should be considered.
$T_{\text{MEM_DCD}}$	150	Duty-cycle distortion.
Tap Uncertainty	0	Tap uncertainty with 75 ps resolution. A window detection error of 75 ps can be on both ends of the window. This is already included in $T_{\text{SAMP_BUFIO}}$.
Total Uncertainties	1180	
Window	320	Worst-case window.

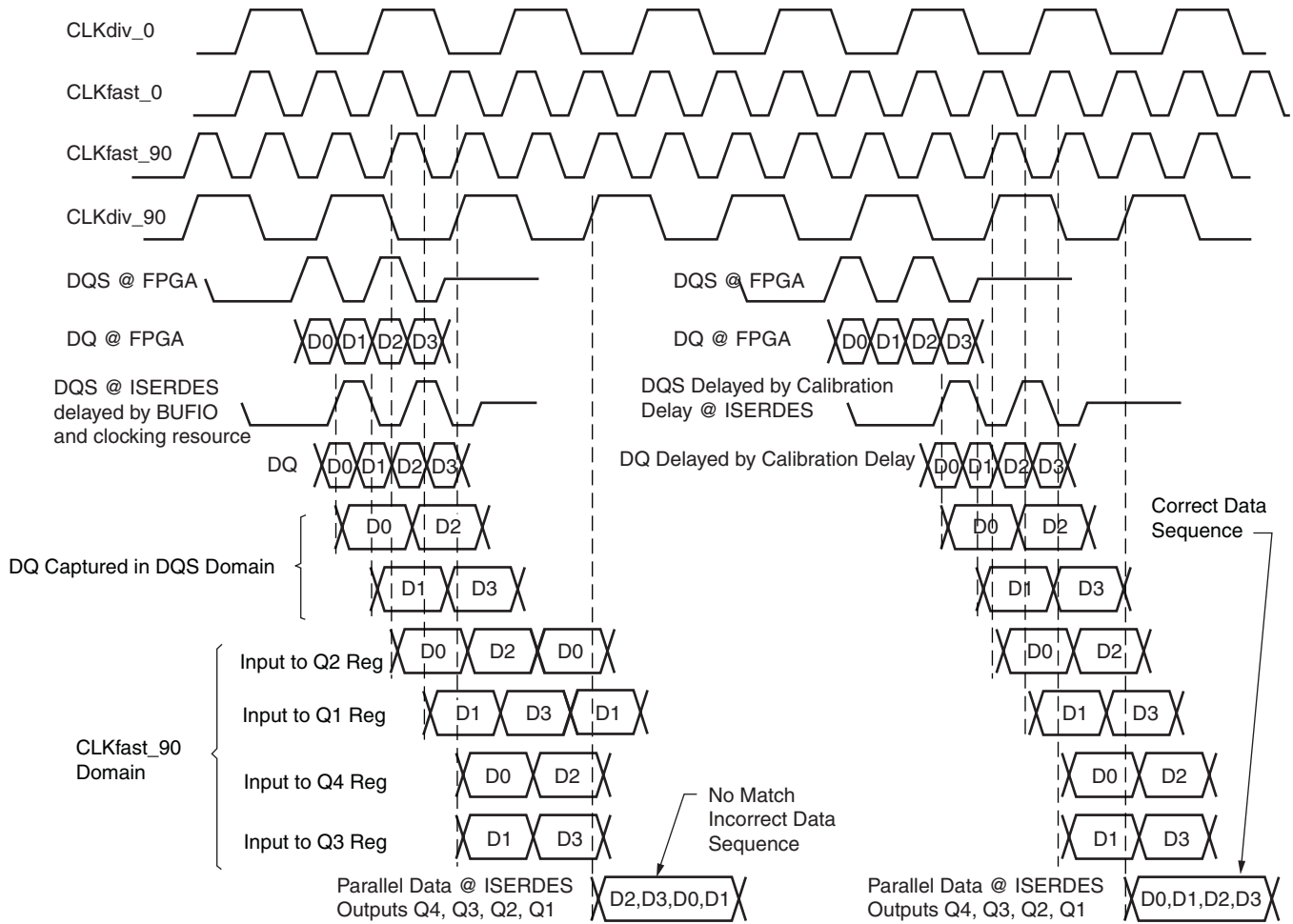
Notes:

1. $T_{\text{SAMP_BUFIO}}$ is the sampling error over VT for a DDR input register in the IOB when using the BUFIO clocking resource and the IDELAY.
2. All the parameters listed above are uncertainties to be considered when using the per bit calibration technique.
3. Parameters like BUFIO skew, package_skew, pcb_layout_skew, and part of TDQSQ, and TQHS are calibrated out with the per bit calibration technique. Inter-symbol interference and crosstalk, contributors to dynamic skew, are not considered in this analysis.

Per Bit Deskew Data Capture Technique

To ensure reliable data capture in the OCLK and CLKDIV domains in the ISERDES, a training sequence is required after memory initialization. The controller issues a WRITE command to write a known data pattern to a specified memory location. The controller then issues back-to-back read commands to read back the written data from this specified location. The DQ bit 0 ISERDES outputs Q1, Q2, Q3, and Q4 are then compared with the known data pattern. If they do not match, DQ and DQS are delayed by one tap, and the comparison is performed again. The tap increments continue until there is a match. If there is no match even at tap 64, then DQ and DQS are both reset to tap 0. DQS tap is set to one, and both DQS and DQ are delayed in unit tap increments and the comparison is performed after each tap increment until a match is found. With the first detected match, the DQS window count is incremented to 1. DQS continues to be delayed in unit tap increments until a mismatch is detected. The DQS window count is also incremented along with the tap increments to record the width of the data valid window in the FPGA clock domain. DQS is then decremented by half the window count to center DQS edges in the center of the data valid window. With the position of DQS fixed, each DQ bit is then centered with respect to DQS. The dp_dly_slct_done signal is asserted when the centering of all DQ bits associated with its DQS is completed.

Figure 8 shows the timing waveform for read data and strobe delay determination. The waveforms on the left show a case where the DQS is delayed due to BUFIO and clocking resource, and the ISERDES outputs do not match the expected data pattern. The waveforms on the right show a case where the DQS and DQ are delayed until the ISERDES outputs match the expected data pattern. The lower end of the frequency range useful in this design is limited by the number of available taps in the IDELAY block, the PCB trace delay, and the CAS latency of the memory device.



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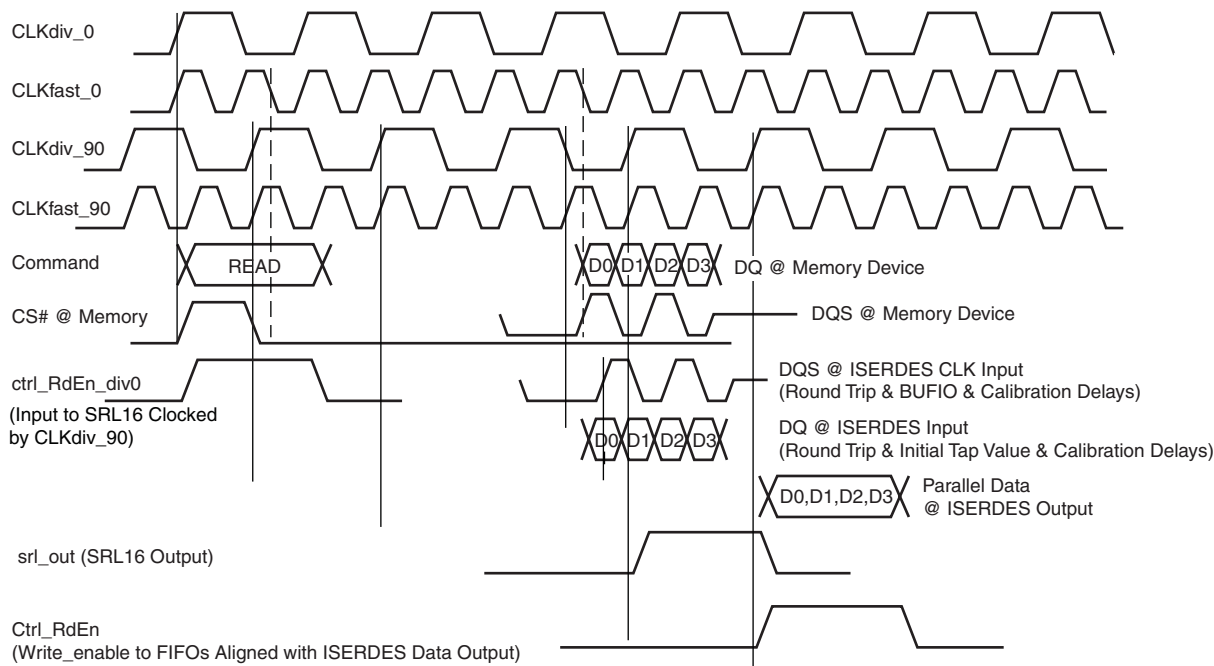
Figure 8: Read Data and Strobe Delay

Controller to Read Datapath Interface

Table 4 lists the control signals between the controller and the read datapath.

Table 4: Signals between Controller and Read Datapath

Signal Name	Signal Width	Signal Description	Notes
ctrl_Dummyread_Start	1	Output from the controller to the read datapath. When this signal is asserted, the strobe and data calibration begin.	This signal must be asserted when valid read data is available on the data bus. This signal is deasserted when the dp_dly_slct_done signal is asserted.
dp_dly_slct_done	1	Output from the read datapath to the controller indicating the strobe and data calibration are complete.	This signal is asserted when the data and strobe have been calibrated. Normal operation begins after this signal is asserted.
ctrl_RdEn_div0	1	Output from the controller to the read datapath used as the write enable to the read data capture FIFOs.	This signal is asserted for one CLKdiv_0 clock cycle for a burst length of 4 and two clock cycles for a burst length of 8. The CAS latency and additive latency values determine the timing relationship of this signal with the read state. Figure 9 shows the timing waveform for this signal with a CAS latency of 5 and an additive latency of 0 for a burst length of 4.



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Figure 9: Read-Enable Timing for CAS Latency of 5 and Burst Length of 4

The ctrl_RdEn signal is required to validate read data because the DDR2 SDRAM devices do not provide a read valid or read-enable signal along with read data. The controller generates this read-enable signal based on the CAS latency and the burst length. This read-enable signal is input to an SRL16 (LUT-based shift register). The number of register stages required to align the read-enable signal to the ISERDES read data output is determined during calibration. One read-enable signal is generated for each data byte. Figure 10 shows the read-enable logic block diagram.

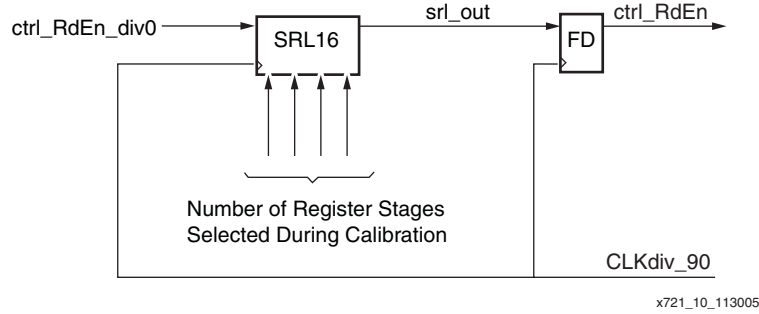


Figure 10: Read-Enable Logic

Reference Design

Figure 11 shows the hierarchy of the reference design. The mem_interface_top is the top-level module. This reference design is available on the Xilinx website at: <http://www.xilinx.com/bvdocs/appnotes/xapp721.zip>.

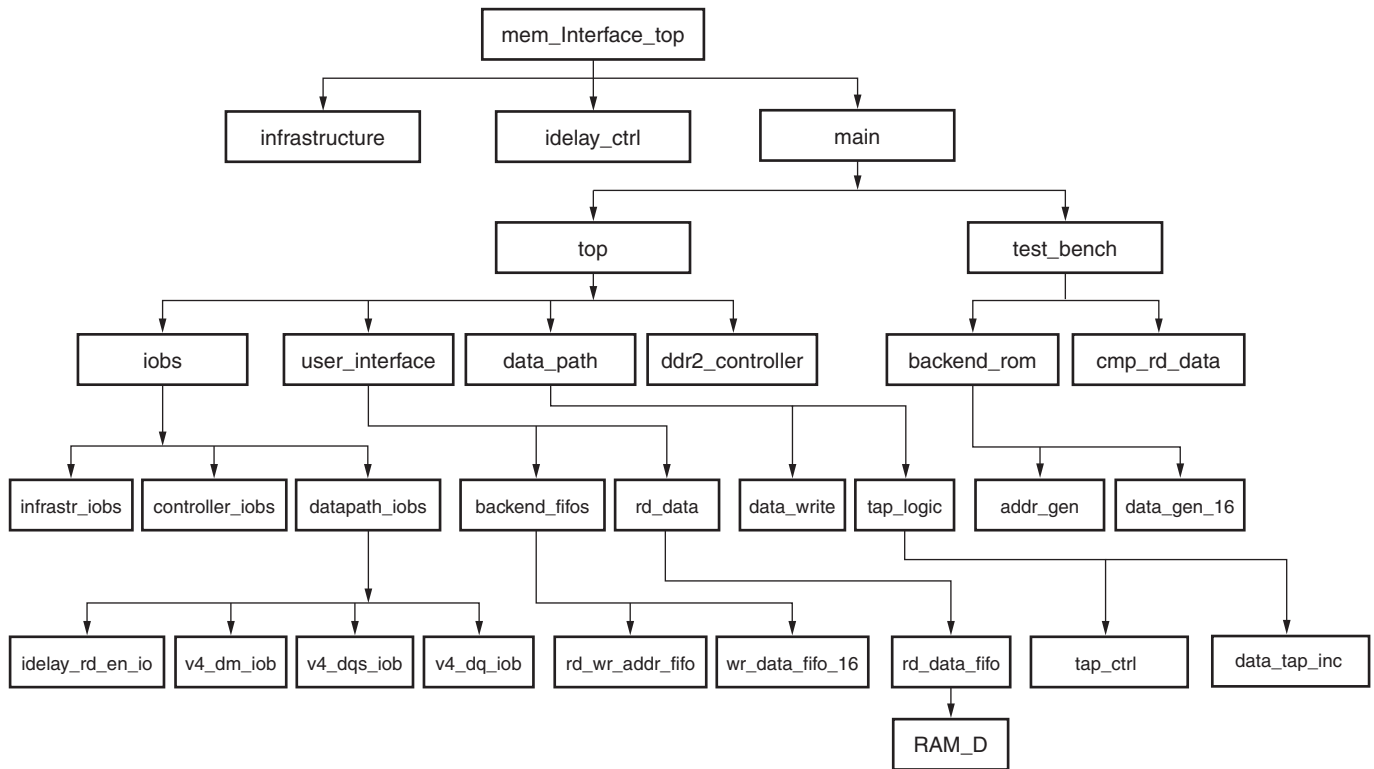


Figure 11: Reference Design Hierarchy

Reference Design Utilization

[Table 5](#) lists the resource utilization for a 64-bit interface including the physical layer, the controller, the user interface, and a synthesizable test bench.

Table 5: Resource Utilization for a 64-Bit Interface

Resources	Utilization	Notes
Slices	5861	Includes the controller, synthesizable test bench, and the user interface.
BUFGs	6	Includes one BUFG for the 200 MHz reference clock for the IDELAY block.
BUFIOs	8	Equals the number of strobes in the interface.
DCMs	1	
PMCDs	2	
ISERDES	64	Equals the number of data bits in the interface.
OSERDES	88	Equals the sum of the data bits, strobes, and data mask bits.

Conclusion

The data capture technique explained in this application note using ISERDES provides a good margin for high-performance memory interfaces. The high margin can be achieved because all the logic in the FPGA fabric is clocked at half the frequency of the interface, eliminating critical paths.

Revision History

The following table shows the revision history for this document.

Date	Version	Revision
12/15/05	1.0	Initial Xilinx release.
12/20/05	1.1	Updated Table 1 .
01/04/06	1.2	Updated link to reference design file.
02/02/06	1.3	Updated Table 4 .